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GAS TURBINE AND JET ENGINE FUELS

PROGRESS REPORT NO. 2

NAVY BUWEPS CONTRACT NOw 63-0406-d

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PHILLIPS 66

PHILLIPS PETROLEUM COMPANY

PHILLIPS PETROLEUM COMPANY - RESEARCH DIVISION REPORT 3615-63R
Feature No. 6058

Progress Report No. 2

Navy BuWep Contract NO w63-0406-d

GAS TURBINE AND JET ENGINE FUELS

By

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William L. Streets

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SUMMARY

Efforts carried on during the second quarterly period under Contract NO w63-0406-d have included: (1) endurance testing of two promising new splash-cooled two-inch test combustor designs capable of operating under conditions simulating low-level tactical fighter attack missions and/or submarine search missions by a regenerative turboprop-equipped aircraft; (2) planning and statistical design of a test program to determine whether the 0.4 weight per cent maximum total sulfur now allowed in JP-5 fuel is a safe level for protection of modern turbine blading alloys from hot gas corrosion and, if not, data will be obtained to show whether lower sulfur limits will alleviate corrosion significantly. These studies will be carried on with and without ingested sea water to show whether or not fuel sulfur accelerates sea salt corrosion.

This report describes the combustor design selected for this work and its performance and explains the test program planned and the information to be gained from it.

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Research Division Report 3615-63R

PHILLIPS PETROLEUM COMPANY

BARTLESVILLE, OKLAHOMA

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Navy BuWep Contract NO w63-0406-d

GAS TURBINE AND JET ENGINE FUELS

I. INTRODUCTION

During the second quarterly period under Contract NO w63-0406-d work has included: (1) endurance testing of two promising new two-inch test combustor designs capable of operating under conditions simulating a low-level attack mission by a naval tactical fighter and/or submarine search and surveillance mission by a regenerative turboprop-equipped aircraft, and (2) statistical design of a test program to determine whether the 0.4 weight per cent maximum total sulfur currently allowed in JP-5 fuel is a safe level for protection of modern turbine blading alloys from hot gas corrosion; if not, information will be obtained to show whether lower sulfur limits would alleviate corrosion significantly. These studies will be conducted with and without ingested sea water to show whether sulfur in the fuel accelerates sea salt corrosion. It is intended that the resulting program will be carried on using the better of the new combustor designs operating under conditions simulating the flight regimes described above. It is the purpose of this report to describe the combustor design selected for this work and its performance and to explain the test program planned and the information to be gained from the program.

II. EVALUATION OF NEW 2-INCH COMBUSTOR DESIGNS

As previously mentioned in Progress Report No. 1, attempts to operate the existing Phillips 2-Inch Research Combustor under conditions simulating an attack mission by a naval tactical fighter resulted in catastrophic failures of combustor liners. Various simple changes were tried without success. At this point it became clear that this combustor was not satisfactory for operation under these conditions. Operations with this combustor were suspended and combustor redesign studies were initiated.

Sixteen individual configurations were evaluated in the combustor development program. Of these sixteen two were selected for endurance testing. Details of the design of the combustor finally selected are shown in Table I and its performance in Table II. A schematic drawing of this combustor together with associated equipment to be used in turbine blading corrosion studies is shown in Figure I. It will be noted that this design differs sharply from previous Phillips 2-inch test combustors in the use of "splash cooling", accomplished by blanketing the inner surface of the Inconel flame tube with a film of air.

Perhaps the degree of difficulty in developing a durable 2-inch combustor for use at these extreme conditions can be realized by pointing out that the so-called "cooling" air flowing through the splash rings enters the combustor at red-heat metal temperature. As seen in Table II, the selected design has completed ten hours of operation at 1200 F inlet air temperature (deliberately made 200 F more severe than the desired operating temperature of 1000 F in order to provide for growth and safety margins), 450 in. Hg abs. combustor pressure, 225 ft/sec. reference velocity and 2000 F exhaust gas temperature. No damage to the liner was visible, and its weight loss was less than 0.1 per cent. This near perfect durability and excellent exhaust gas temperature profile are important to the use of the combustor in evaluating sulfur-sea water corrosion of turbine blades. This corrosion study, to be subsequently discussed herein, will be possible now that a suitable combustor is available.

It should be noted from Figure 1 that means for measuring the surface temperature of turbine inlet guide vane test strips as well as exhaust gas temperature have been incorporated into the Phillips 2-Inch Combustor. This will be done by sighting through the two sight tubes to the hot test strips using an optical pyrometer. Trial tests using this technique have proven successful. This method circumvents the inevitable problems associated with attachment of thermocouples to the test specimens, etc.

III. DESIGN OF HOT GAS CORROSION TEST PROGRAM

As previously mentioned, efforts during this reporting period have included planning of a statistical block test program which is designed to yield data on the effects of sulfur/sea water corrosion under conditions simulating a low-level tactical fighter mission and/or a regenerative turbo-prop-equipped submarine search aircraft. The operating conditions selected for this program are as follows:

Combustor Pressure = 450 in. Hg abs.

Inlet Reference Velocity = 200 ft/sec.

Inlet Air Temperature = 1000 F

Average Exhaust Gas Temperature = 2000 F

The operating cycle for these tests will be 55 minutes at the above conditions followed by 5 minutes of shutdown time. This cycle will be repeated for a total of 10 hours test time. The base fuel selected for the program is a West Texas production ASTM Type A turbine fuel containing 0.0002 weight per cent sulfur.

From the standpoint of fuel variables, the prime information desired from the program is whether or not the 0.4 weight per cent maximum total sulfur currently allowed in JP-5 fuel is a safe level with regard to the durability of "hot section" components, particularly under conditions favoring the ingestion of sea water. Information should also be obtained to show whether or not lower sulfur limits would alleviate corrosion significantly (with and without sea water ingestion) should the 0.4 per cent level prove unsafe. Additionally, the corrosiveness of ingested sea water per se (little or no sulfur in fuel) should be established.

It is believed that the statistical block program shown below will meet the above described objectives as well as provide evaluation of five superalloys which are currently of maximum interest for application in high temperature sulfur/sea salt laden environments:

	No Sea Water			15 Parts Ingested Sea Salt, per Million Parts Combustor Total Mass Throughput		
Alloy	0.0002% Sulfur Fuel*	0.04% Sulfur Fuel**	0.4% Sulfur Fuel***	0.0002% Sulfur Fuel*	0.04% Sulfur Fuel**	0.4% Sulfur Fuel***
Sierra Metal 200	8	4	10	2	11	7
	6	3	1	5	9	12
Sierra Metal 302	5	8	6	4	10	9
	11	3	7	1	2	12
Inconel 713C	6	1	7	10	4	3
	8	12	9	11	5	2
Udimet 700	3	8	11	12	2	4
	9	7	1	10	6	5
Stellite 31	2	3	10	9	4	6
	7	1	12	11	5	8

*Base Fuel
**Base Fuel plus sufficient ditertiary butyl disulfide to yield 0.04% total sulfur.
***Base Fuel plus sufficient ditertiary butyl disulfide to yield 0.04% total sulfur.

(Note: Numbers indicate order of running of tests.)

It will be noted from inspection of the block that the order of running of the tests has been randomized for tests on a given alloy. Ideally, the complete block would be randomized but in this case it was decided to complete testing of each alloy before proceeding to the next alloy in order to be assured of having coherent data packages in the least time. Statistica analysis of the data for each metal will yield variance estimates permitting tests for significance of the following effects:

Effect	Degrees of Freedom
Fuel Sulfur Content	2
Sea Water Ingestion (with and without)	1
Interaction Between Sulfur and Sea Water	2
Repeatability	6

If, upon completion of the evaluation of all the alloys, it can be shown by statistical tests that the standard deviations computed from the data on each alloy differ only by amounts expected by chance alone (a not unlikely result) the entire block of data may be pooled to yield the following:

Effect	Degrees of Freedom
Fuel Sulfur Content	2
Sea Water Ingestion (w/and w/o)	1
Alloy Type	4
Interaction: Sulfur-Sea Water	2
Interaction: Sulfur-Alloys	8
Interaction: Sea Water-Alloys	4
Interaction: Sulfur-Sea Water-Alloys	8
Repeatability	30

Although this analysis will be based principally upon measurements of weight loss, it is planned also to obtain other measurements such as loss in tensile strength and ductility, hardness and others as deemed desirable. Metallographic information will be obtained as supporting evidence in those cases where it appears useful and/or desirable.

As was done in obtaining the weight loss data reported in Progress Report No. 1, the turbine guide vane test specimens will be descaled cathodically in molten caustic soda at the end of each ten-hour run prior to reweighing. This will be carried on according to the technique outlined in (4).

IV. OUTLINE OF PLANNED FUTURE EFFORTS

It is planned to carry on testing as per the program outlined in III, above, during the third quarterly period under Contract NO w63-0406-d. Testing will be started using Inconel 713C investment cast test specimens which are now on hand. Testing with other alloys will follow in whatever order they become available from the casting supplier.

Work will also be started, during the third quarterly period, on a study of the relationship between hydrocarbon structure and flame radiation in aircraft gas turbine type combustion processes. Forty-four pure hydrocarbons have been obtained for this study, and are listed in Table III with presently available physical and chemical properties of pertinence. The variation in Luminometer Number and hydrogen content over the boiling point range of these test fuels is shown in Figures 2 and 3 respectively. Initial measurements of total radiant energy from their flames, when burned in Phillips Microburner, will be made using Leeds & Northrup Rayotubes. The Microburner will be operated over a broad range of fuel-air mixture ratios, simulating premixed turbulent flames to diffusion turbulent flames. A dual channel Barnes Research Radiometer is also being modified for measurement of both total flame radiant energy and radiant energy at the 4.4 micron CO_2 peak for determination of flame emissivity.

REFERENCES

1. Streets, W. L., and Schirmer, R. M.; "Gas Turbine and Jet Engine Fuels", Summary Report, Navy BuWep Contract N600(19)-58219, Phillips Research Division Report 3529-63R.

2. Fromm, E. H.; "Design and Calibration of the Improved Phillips Jet Fuel Testing Facilities", Phillips Research Division Report 3527-63R.

3. Streets, W. L.; "Gas Turbine and Jet Engine Fuels", Progress Report No. 1, Navy BuWep Contract NO w63-0406-d, Phillips Research Division Report 3559-63R.

4. Shirley, H. T.; "Effects of Sulfate-Chloride Mixtures in Fuel-Ash Corrosion of Steels and High-Nickel Alloys", Journal of the Iron and Steel Institute, 1956, Volume 182, pp. 144-153.

TABLE I

DESIGN DETAILS OF PHILLIPS 2-INCH COMBUSTOR FOR OPERATION AT SIMULATED SUPERSONIC FLIGHT CONDITIONS FOR STUDY OF EXHAUST PRODUCT CORROSION

Configuration No. 15: (See also Figure 1)

Splash Cooling Air	
Hole Diameter, in.	0.125
Holes/Station	16
No. of Stations	7
Total No. of Holes	112
Total Hole Area, $in.^2$	1.38
% Total Hole Area	42
Primary Combustion Air	
Hole Diameter, in.	0.250
Total No. of Holes	4
Total Hole Area, $in.^2$	0.20
% Total Hole Area	6
Secondary Combustion Air	
Hole Diameter, in.	0.375
Total No. of Holes	4
Total Hole Area, $in.^2$	0.44
% Total Hole Area	14
Quench Air	
Hole Diameter, in.	0.625
Total No. of Holes	4
Total Hole Area, $in.^2$	1.22
% Total Hole Area	38
Total Combustor Area, $in.^2$	3.24
% Cross Sectional Area	122
Fuel Nozzle and Combustor Dome	
Spray Angle, degrees	45
Shield Hole Diameter, in.	0.625
Air Atomizer Swirl Plate?	Yes

TABLE II

PERFORMANCE OF PHILLIPS 2-INCH SPLASH-COOLED COMBUSTOR (CONFIGURATION 15)

UNDER SIMULATED SUPERSONIC FLIGHT CONDITIONS

Operating Conditions: Combustor Pressure = 450 in.Hg abs; Reference Velocity = 225 ft/sec.; Inlet Air Temp. = 1200 F

Operating Cycle: 55 minutes at above conditions followed by 5 minutes shutdown.

Running Time, hr/min.	0	1:55	3:55	5:55	7:55	9:55
Air Flow, lb/sec.	1.57	1.57	1.57	1.57	1.57	1.57
Fuel Flow, lb/hr.	76.0	79.5	79.5	79.5	80.5	80.5
Exhaust Gas Temp., F						
T.C. #1 (Wall)	2100	2140	2010	2070	2030	2000
T.C. #2	1950	2000	2010	2030	2000	1980
T.C. #3	1810	1850	1910	1900	1920	1930
T.C. #4 (Core)	1930	1960	1970	1960	1960	1970
Average	1947	1987	1975	1990	1977	1970
Combustor Temp. Rise, F	747	787	775	790	777	770
Combustion Efficiency, %	88	90	87	90	88	88
Combustor Pressure Drop Inches Hg	19.0	22.0	21.5	23.0	23.0	22.5
Combustor Liner Metal Loss, %	—	0.025	—	0.055	—	0.079
Exhaust Gas Temp. Profile (ΔT), F	290	290	100	170	110	70

TABLE III

PURE HYDROCARBONS FOR STUDY OF RELATIONSHIP BETWEEN THEIR MOLECULAR STRUCTURE AND FLAME RADIATION INTENSITY UNDER NAVY BUWEP CONTRACT NOw 63-0406-d.

A. NORMAL PARAFFINS

Sample Number BJ63-8-	Compound		Formula	Purity, Mol %	Boiling Point, F	API Gravity @ 60 F	Aniline Point, F	Refractive Index @ 68 F	Net Heat of Combustion, BTU/lb	Hydrogen Content, wt %	Luminometer Number	Smoke Point, mm
A13	Normal Hexane	Estimated	C_6H_{14}	99	156	81.6	155.5	1.3749	19,233	16.37	240	Over 50
		Measured				81.6		1.3759				
A10	Normal Heptane		C_7H_{16}	99	209	74.1	157.5	1.3876	19,157	16.10	224	Over 50
						74.1		1.3883				
A17	Normal Octane		C_8H_{18}	99	258	68.7	159.1	1.3974	19,100	15.88	205	Over 50
						65.7		1.3970				
A32	Normal Decane		$C_{10}H_{22}$	99	345	61.3	170.6	1.4119	19,020	15.59	175	Over 50
A33	Normal Dodecane		$C_{12}H_{26}$	99	421	56.5	------	1.4216	18,966	15.39	158	Over 50
A34	Normal Tetradecane		$C_{14}H_{30}$	99	488	53.1	------	1.4289	18,927	15.24	148	Over 50
A29	Normal Hexadecane (Cetane)		$C_{16}H_{34}$	99	548	----	------	1.4355	18,898	15.13	135	Over 50
						50.9		1.4350				
A4	n-Decane - n-Pentadecane Mixture			99	(425)	55.8		1.4213		(15.3)	(150)	Over 50
				98.5	421*	56.0		1.4228				
A35	n-Decane Concentrate		$C_{10}H_{22}$	(80)	(345)	(57.0)	(159.9)	(1.4203)	(18,888)	(15.6)	(150)	Over 50
				84.7	338*	56.9	169.1	1.4191				
A36	n-Decane - n-Pentadecane Concentrate			80	(425)					(15.3)	(120)	Over 50
					426*	52.6	170.4	1.4291				

NOTE: * indicates volumetric average boiling point.

TABLE III (continued)

PURE HYDROCARBONS FOR STUDY OF RELATIONSHIP BETWEEN THEIR MOLECULAR STRUCTURE AND FLAME RADIATION INTENSITY UNDER NAVY BUWEP CONTRACT NOw 63-0406-d.

B. ISOPARAFFINS

Sample Number BJ63-8-	Compound		Formula	Purity, Mol %	Boiling Point, F	API Gravity @ 60 F	Aniline Point, F	Refractive Index @ 68 F	Net Heat of Combustion, BTU/lb	Hydrogen Content, wt %	Luminometer Number	Smoke Point, mm
A18	3-Methylpentane	Estimated	C_6H_{14}	99	146	80.0		1.3765	19,218	16.37	165	Over 50
		Measured				80.4		1.3770				
A37	2,2-Dimethylbutane (Neohexane)		C_6H_{14}	99	123	84.9		1.3688	19,161	16.37	(113)	(45)
A8	2,3-Dimethylbutane (Diisopropyl)		C_6H_{14}	99	136	80.8		1.3750	19,192	16.37	133	Over 50
						80.0	140.7	1.3742				
A38	Dimethylhexanes (Mixed 2,3- and 2,5-)		C_8H_{18}	99	(229)	(70.3)		(1.3945)	(19,075)	15.88	(131)	Over 50
					225*	70.3		1.3948				
A9	2,2,4-Trimethylpentane (Isooctane)		C_8H_{18}	99	211	71.7	175.1	1.3915	19,065	15.88	100	(42)
						71.7		1.3923				41.6
A20	2,3,4-Trimethylpentane		C_8H_{18}	99	236	64.1		1.4042	19,080	15.88	120	(50)
						64.3		1.4050				
A30	2,2,4,4,6,8,8-Heptamethylnonane		$C_{16}H_{34}$	99	(530)					15.13	(100)	(42)
					458*	48.0		1.4402				
B6	Isoundecanes (Soltrol 130)		$C_{11}H_{24}$	98	(364)	(56.2)	(185)	(1.4217)		15.48	(105)	(43)
					366*	55.3	184.4	1.4235				41.8
B7	Isotridecanes (Soltrol 170)		$C_{13}H_{28}$	97	(437)	(51.2)	(196)	(1.4315)		15.31	(100)	(42)
					435	50.6	194.6	1.4336				38.7

TABLE III (continued)

PURE HYDROCARBONS FOR STUDY OF RELATIONSHIP BETWEEN THEIR MOLECULAR STRUCTURE AND FLAME RADIATION INTENSITY UNDER NAVY BUWEP CONTRACT NOw 63-0406-d.

C. CYCLOPARAFFINS

Sample Number BJ63-8-	Compound		Formula	Purity, Mol %	Boiling Point, F	API Gravity @ 60 F	Aniline Point, F	Refractive Index @ 68 F	Net Heat of Combustion, BTU/lb	Hydrogen Content, wt %	Luminometer Number	Smoke Point, mm
A14	Cyclohexane	Estimated	C_6H_{12}	99	177	49.1	87.8	1.4262	18,676	14.37	130	Over 50
		Measured				49.9		1.4264				
A21	Methylcyclopentane		C_6H_{12}	99	161	56.2	91.4	1.4097	18,768	14.37	76	(33)
						56.8		1.4098				33.9
A19	1,2-Dimethylcyclohexanes (Mixed Isomers)		C_8H_{16}	99	(260)	(48)		(1.431)	(18,650)	14.37	(84)	(36)
A39	Diethylcyclohexanes		$C_{10}H_{20}$		(340)					14.37	(88)	(37)
				95.7	339*	44.3	132.3	1.4401				35.9
A40	Deca-Hydro naphthalene (Decalin) (Mixed Isomers)		$C_{10}H_{18}$	(99)	(374)	(27.3)		(1.468)	(18,325)	13.20	(48)	(22)
				98.7	372*	27.7	92.8	1.4764				22.9
A41	Methyl deca-hydro naphthalenes (Methyl decalins)		$C_{11}H_{20}$		(418)					13.24	(47)	(22)
				99.6	418*	33.9	130.2	1.4644				21.4
A42	Tetracyclo dodecane (Dimethanodecalin)		$C_{12}H_{18}$	(99)	(458)	(10)			(18,120)	11.15	(18)	(10)
				99.3	446*	7.1	87.7	1.5200				10.9
A43	Isopropyl bicyclohexyl		$C_{15}H_{28}$	(99)	(542)	(28)			(18,425)	13.54	(58)	(26)
				96.5	531*	27.9	142.2	1.4825				23.0

TABLE III (continued)

PURE HYDROCARBONS FOR STUDY OF RELATIONSHIP BETWEEN THEIR MOLECULAR STRUCTURE AND FLAME RADIATION INTENSITY UNDER NAVY BUWEP CONTRACT NOw 63-0406-d.

D. OLEFINS

Sample Number BJ63-8-	Compound		Formula	Purity, Mol %	Boiling Point, F	API Gravity @ 60 F	Aniline Point, F	Refractive Index @ 68 F	Net Heat of *Combustion, BTU/lb	Hydrogen Content, wt %	Luminometer Number	Smoke Point, mm
A22	1-Hexene	Estimated	C_6H_{12}	99	146	77.2	73.0	1.3879	19,132	14.37	105	(43)
		Measured				77.4		1.3889				40.1
A44	1-Octene		C_8H_{16}	99	250	65.1	90.5	1.4087	19,033	14.37	110	(45)
A23	4-Methyl-2-pentene (Mixed Isomers)		C_6H_{12}	99	(135)	(78.5)		(1.388)	(19,050)	14.37	(90)	(37)
						78.5		1.3889				28.3
A45	2,4,4-Trimethyl-1-pentene (Diisobutylene)		C_8H_{16}	99	215	65.2		1.4086	18,904	14.37	(60)	(27)
A12	Cyclohexene		C_6H_{10}	99	181	41.9	-4.0	1.4465	18,483	12.27	71	(31)
						42.4		1.4470				31.1
A24	4-Vinyl-cyclohexene-1		C_8H_{12}	99	262	37.7		1.4641		11.18	(50)	(23)
						38.2		1.4641				18.8
A46	Phenylethylene (Styrene)		C_8H_8	99	293	23.8		1.5468	17,418	7.74	(-15)	(5)
						24.2	Below -10	1.5469				6.2

TABLE III (continued)

PURE HYDROCARBONS FOR STUDY OF RELATIONSHIP BETWEEN THEIR MOLECULAR STRUCTURE AND FLAME RADIATION INTENSITY UNDER NAVY BUWEP CONTRACT NOw 63-0406-d.

E. AROMATICS

Sample Number BJ63-8-	Compound		Formula	Purity, Mol %	Boiling Point, F	API Gravity @ 60 F	Aniline Point, F	Refractive Index @ 68 F	Net Heat of Combustion, BTU/lb	Hydrogen Content, wt %	Luminometer Number	Smoke Point, mm
A11	Benzene	Estimated	C_6H_6	99	176	28.4		1.5011	17,259	7.74	11	(8)
		Measured				29.0	Below -2	1.5011				8.1
A15	Methylbenzene (Toluene)		C_7H_8	99	231	30.8		1.4969	17,424	8.75	3	(6)
						31.4	Below -40	1.4974				7.7
A25	1,4-Dimethylbenzene (Para-Xylene)		C_8H_{10}	99	281	31.9	-22	1.4958	17,547	9.50	-2	(6)
						32.3		1.4960				7.4
A26	Ethylbenzene		C_8H_{10}	99	277	30.8		1.4959	17,596	9.50	2	(6)
						31.2		1.4959				6.8
A47	Diethylbenzene (Mixed Isomers)		$C_{10}H_{14}$	99	(360)	(30)		(1.495)		10.51	4	(6)
					352*	31.5	Below 2	1.4959				6.6
A27	sec-Butylbenzene (2-Phenylbutane)		$C_{10}H_{14}$	99	344	31.5		1.4902	17,851	10.51	15	(10)
						32.3		1.4900				8.2
A16	Tetra-Hydro-naphthalene (Tetralin)		$C_{10}H_{14}$	99	(412)	(14)		1.5438		10.51	0	(6)
					397*	14.6	Below -24	1.5395				6.6
A31	1-Methylnaphthalene		$C_{11}H_{10}$	99	472	(8)		1.6149	(16,700)	7.39	-14	(5)
						7.3		1.6151				5.1
A48	Methylnaphthalene Concentrate (Mixed Isomers)		$C_{11}H_{10}$	(75)	(472)	(8)			(16,700)	(7.09)	(-14)	(5)
					460*	6.8	Below -60	1.6142				5.0

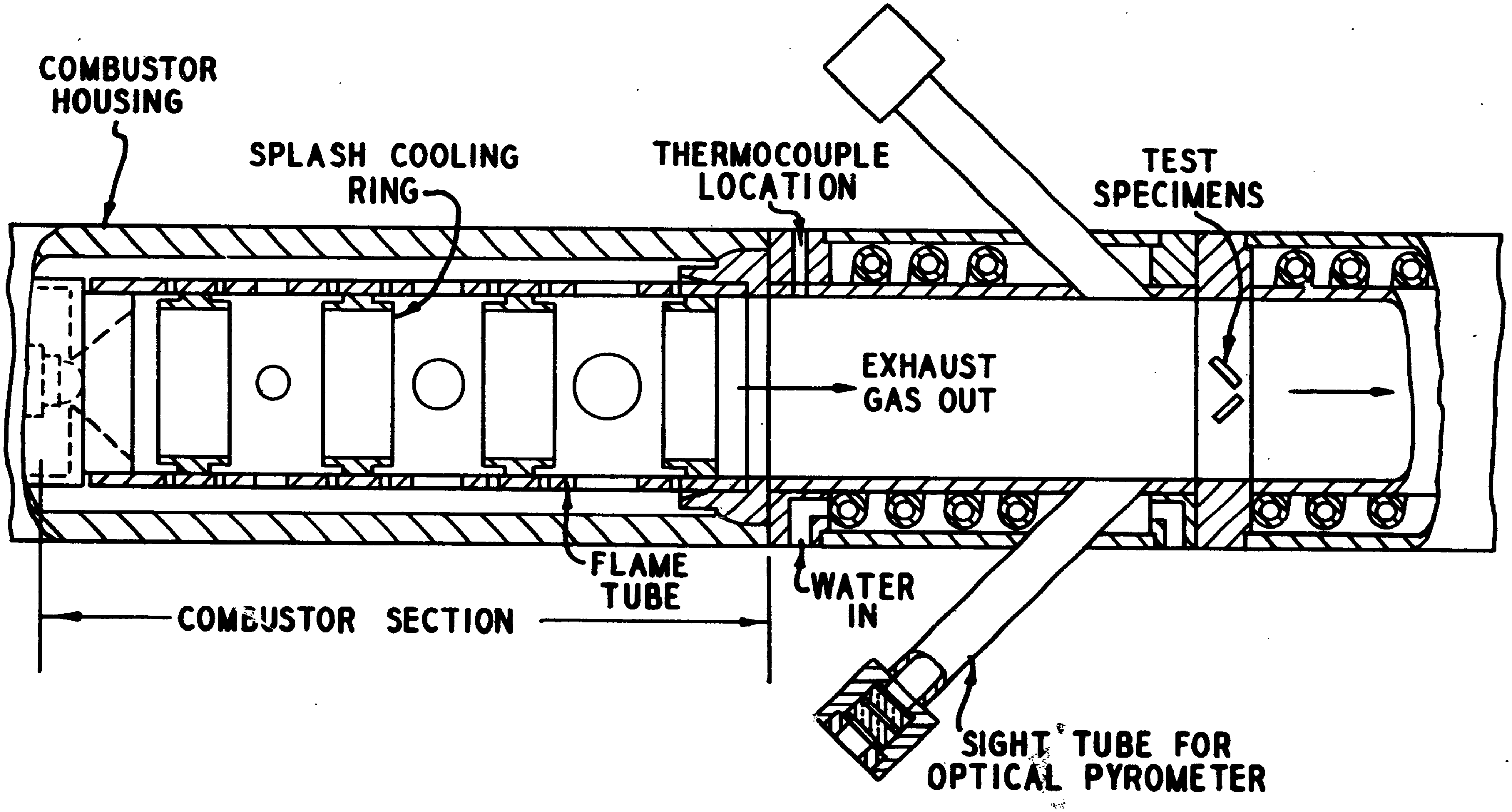

FIG. 1
PHILLIPS LABORATORY SCALE TEST COMBUSTOR

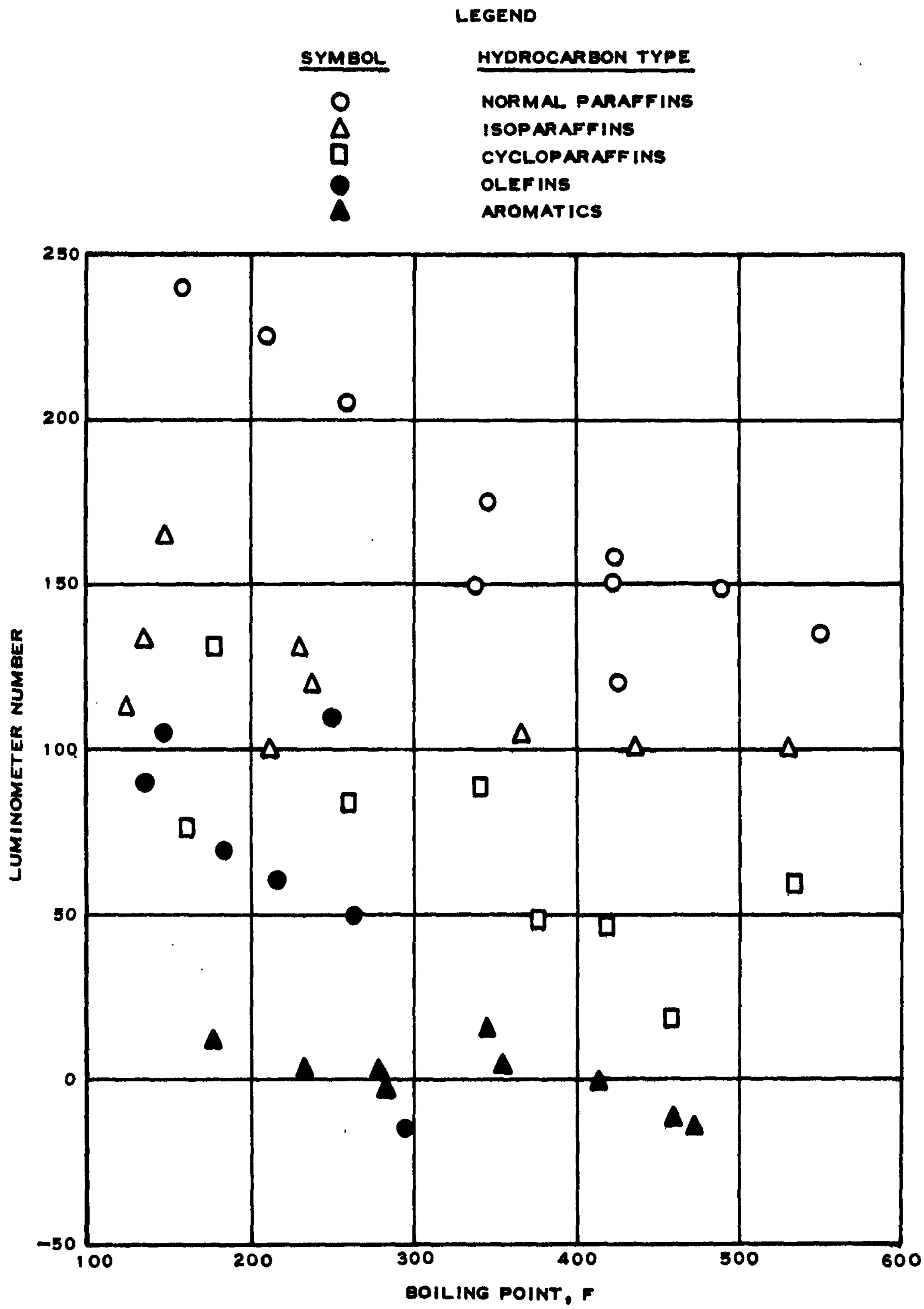

FIGURE 2
SPREAD IN LUMINOMETER NUMBER OVER BOILING POINT RANGE OF PURE HYDROCARBONS SELECTED FOR STUDY OF RELATIONSHIP BETWEEN FUEL MOLECULAR STRUCTURE AND FLAME RADIATION INTENSITY IN AIRCRAFT GAS TURBINE TYPE COMBUSTION PROCESSES

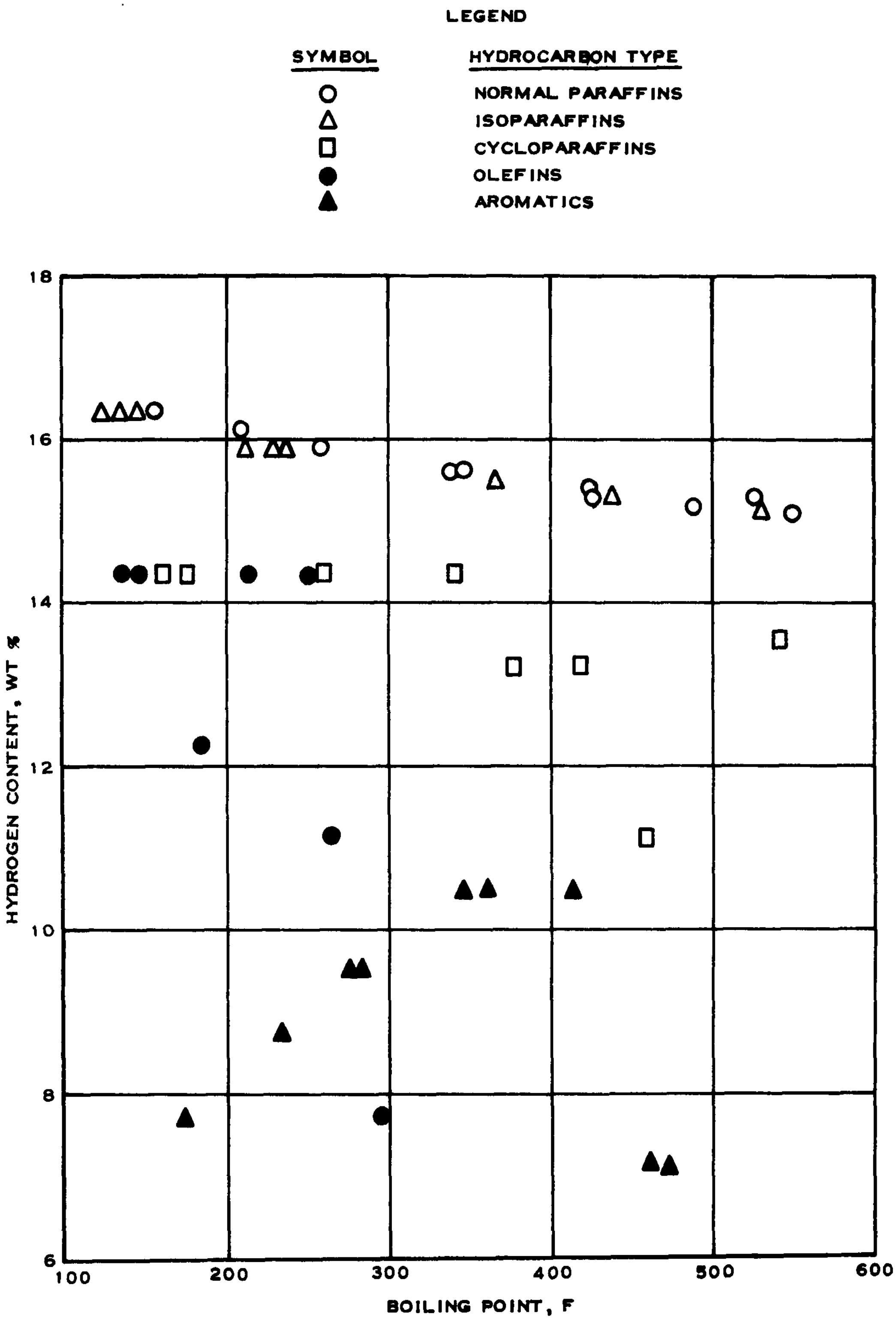

FIGURE 3
SPREAD IN HYDROGEN CONTENT OVER BOILING POINT RANGE OF PURE HYDROCARBONS SELECTED FOR STUDY OF RELATIONSHIP BETWEEN FUEL MOLECULAR STRUCTURE AND FLAME RADIATION INTENSITY IN AIRCRAFT GAS TURBINE TYPE COMBUSTION PROCESSES